GDC-ASP-81-009

NASA-CR-1674

(NASA-CR-167458) SPACE CONSTRUCTION EXPERIMENT DEFINITION STUDY (SCEDS), PART 1. VOLUME 1: EXECUTIVE SUMMARY Final Report (General Dynamics/Convair) 34 p HC A03/MF A01 CSCL 22A G3/12

N82-12094

Unclas 08430

SPACE CONSTRUCTION EXPERIMENT DEFINITION STUDY (SCEDS) PART I

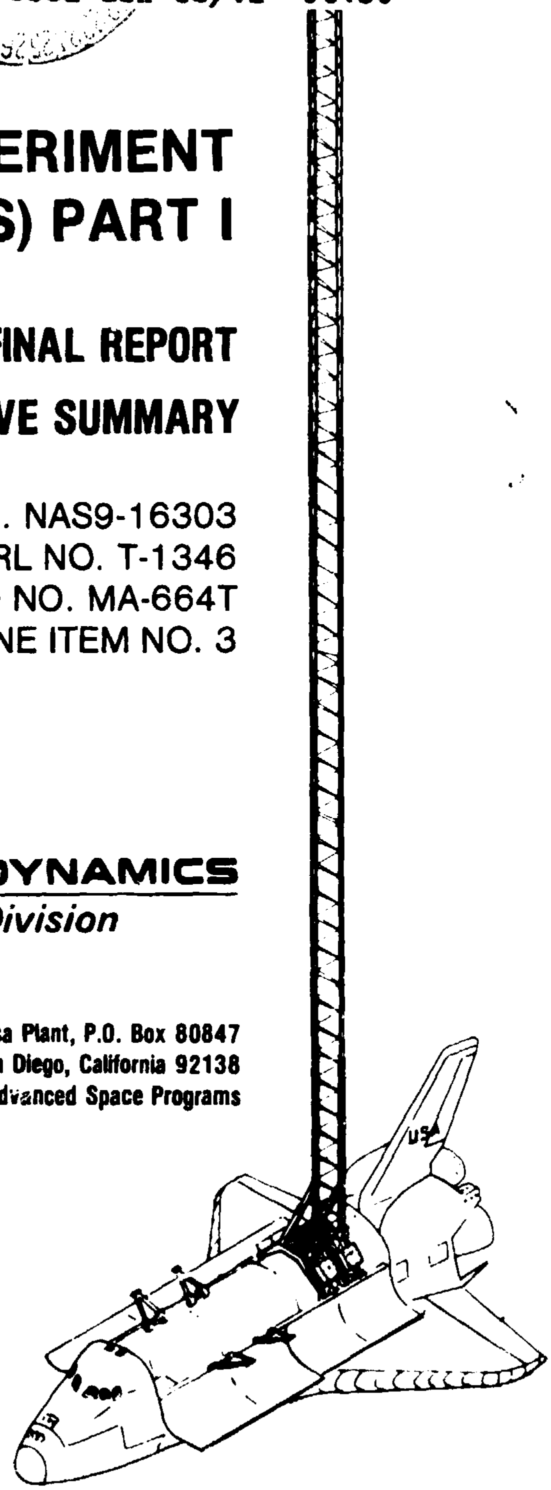
FINAL REPORT

VOLUME I • EXECUTIVE SUMMARY

CONTRACT NO. NAS9-16303
DRL NO. T-1346
DRD NO. MA-664T
LINE ITEM NO. 3

GENERAL DYNAMICS
Convair Division

Kearny Mesa Plant, P.O. Box 80847
San Diego, California 92138
Advanced Space Programs



GENERAL DYNAMICS
Convair Division

Kearny Mesa Plant, P.O. Box 80847, San Diego, California 92138 · 714-277-8900
Procurement, P.O. Box 80827
Lindbergh Field Plant, P.O. Box 80877, San Diego, California 92138
Accounting, P.O. Box 80818

110-4-81-955
FJK:r
3 November 1981

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Spacecraft Design Division
Houston, Texas 77058

Attention: Lyle Jenkins/EB

Subject: Contract NAS9-16303

Enclosure: (1) Final Report, Volume I - Executive Summary
Line Item No. 3 (144 copies)

Gentlemen:

The enclosed report is submitted herewith in accordance with the requirements of the subject contract.

Very truly yours,

F. J. Kennie
Contract Administrator

cc: NASA Lyndon B. Johnson Space Center
R&T Procurement Branch
Attn: BC72 (1 copy)
Houston, TX 77058
Mark For: Contract NAS9-16303

NASA Lyndon B. Johnson Space Center
Technical Library Branch
Attn: Mail Code JM6 (4 copies)
Houston, TX 77058
Mark For: Contract NAS9-16303

NASA Lyndon B. Johnson Space Center
Technology Utilization Office
Attn: John T. Wheeler, Mail Code AT3 (1 copy)
Houston, TX 77058
Mark For: Contract NAS9-16303

GDC-ASP-81-009
CONTRACT NO. NAS9-16303
DRL NO. T-1346
DRD NO. MA-664T
LINE ITEM NO. 3

SPACE CONSTRUCTION EXPERIMENT DEFINITION STUDY (SCEDS) PART I

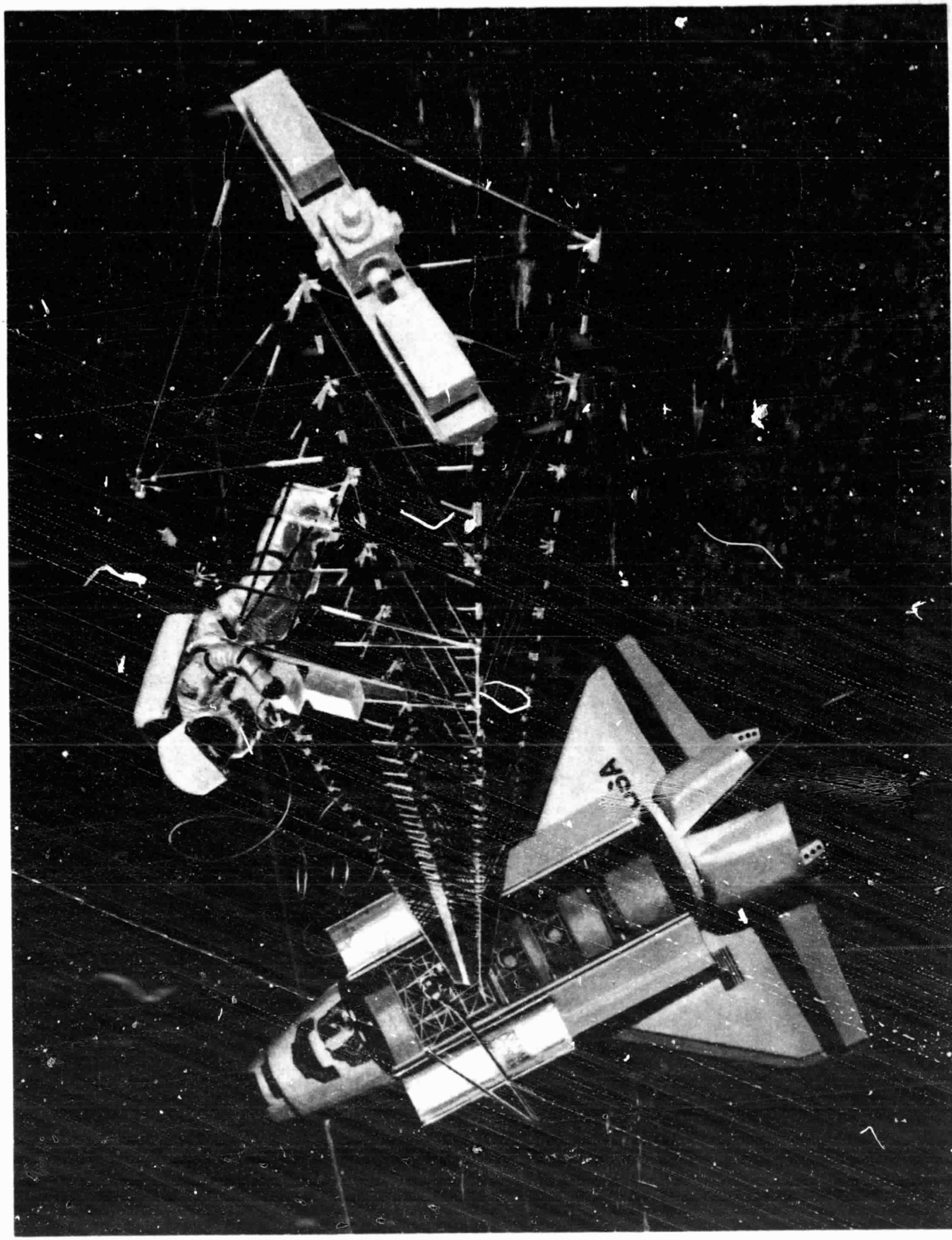
FINAL REPORT

VOLUME I • EXECUTIVE SUMMARY

1 September 1981

Submitted to
National Aeronautics and Space Administration
LYNDON B. JOHNSON SPACE CENTER
Houston, Texas 77058

Prepared by
GENERAL DYNAMICS CONVAIR DIVISION
P.O. Box 80847
San Diego, California 92138



FOREWORD

The final report was prepared by General Dynamics Convair Division for NASA-JSC in accordance with Contract NAS9-16303, DRL No. T-1346, DRD No. MA-664T, Line Item No. 3. It consists of two volumes: (I) a brief Executive Summary and (II) a comprehensive set of Study Results.

The principal study results were developed from February 1981 through July 1981 followed by final documentation. Reviews were presented at JSC on 1 May 1981 and 21 July 1981.

General Dynamics Convair personnel who significantly contributed to the study include:

Study Manager	John Bodle
Control Dynamics	Ray Halstenberg, John Sesak
Mechanical Design	Bela Kainz, Hans Stocker, Tony Vasques
Avionics & Controls	Stan Maki
Operations Analysis	Nebs Tosaya
System Requirements	John Maloney
Structural Design	John Rule, Des Vaughan
Structural Analysis	Bill Bussey
Structural Dynamics	Chris Flanagan, Des Pengelley
Thermodynamics	Dick Pleasant, Dick O'Neill
Mass Properties	Dennis Stachowitz
Economic Analysis	Bob Bradley

The study was conducted in Convair's Advanced Space Programs department, directed by W. F. Rector, III. The NASA-JSC COR is Lyle Jenkins of the Program Development Office, Clark Covington, Chief.

For further information contact:

Lyle M. Jenkins, Code EB
NASA-JSC
Houston, Texas 77058
(713) 483-2478

John G. Bodle, MZ 21-9530
General Dynamics Convair Division
P. O. Box 80847
San Diego, California 92138
(714) 277-8900, Ext. 2815

TABLE OF CONTENTS

Section		Page
1	INTRODUCTION	1-1
1.1	Scope	1-1
1.2	Study Overview	1-1
1.3	Summary	1-1
2	STUDY RESULTS	2-1
2.1	Structure	2-1
2.1.1	Deployable Structures Requirements	2-1
2.1.2	Deployable Structures Evaluation and Selection	2-2
2.2	Construction Operations	2-3
2.2.1	Construction Operations Analysis	2-3
2.2.2	Identification of Tests and Experiments	2-3
2.2.3	Evolutionary Options	2-7
2.3	Concept Selection and Preliminary Design	2-8
2.3.1	STS Flight Candidates Evaluation	2-8
2.3.2	Experiment Concepts and Evaluations	2-8
2.3.3	Preliminary Design	2-10
2.4	Analysis	2-12
2.4.1	Structural Analysis	2-12
2.4.2	Mass Properties	2-14
2.4.3	Thermodynamic Considerations	2-14
2.5	Flight Control Analysis	2-14
2.5.1	Dynamic Testing	2-14
2.5.2	Damping Augmentation	2-15
2.5.3	DAP Considerations	2-16
2.6	Preliminary Test Plan	2-18
2.7	Programmatics	2-20
2.7.1	Program Development Plan	2-20
2.7.2	Program Funding	2-21
3	CONCLUSIONS AND RECOMMENDATIONS	3-1
3.1	Conclusions	3-1
3.1.1	Structure	3-1
3.1.2	Construction Operations	3-1
3.1.3	Preliminary Design	3-1
3.1.4	Analysis	3-1
3.1.5	Flight Control Analysis	3-2
3.1.6	Test Plan	3-2
3.1.7	Program Plan	3-2
3.2	Recommendations	3-2
3.2.1	Systems Design and Analysis	3-2
3.2.2	Flight Control Analysis	3-2
3.2.3	System Test	3-2

LIST OF FIGURES

Figure		Page
1-1	SCEDS Part I Study Approach	1-2
2-1	LSS Candidates for Near Term Applications	2-1
2-2	Candidate Deployable Structure Concepts	2-2
2-3	General Dynamics Prototype Deployable Truss	2-3
2-4	RMS Deploy/Retract Operations and Suitcase Experimental Hardware	2-5
2-5	Preinstalled Conduit Demonstration	2-6
2-6	Subsystem Module Installation Concept	2-6
2-7	EVA/RMS Construction Operations Test Concept	2-6
2-8	SCE Evolutionary Options	2-7
2-9	Alternative SCE Concepts	2-9
2-10	SCE Support Structure and Stowage Envelope	2-10
2-11	Basic Experiment General Arrangement and Characteristics	2-11
2-12	RMS Driven Deployment Mechanisms	2-11
2-13	Deployment/Retraction Carriage Mechanisms	2-11
2-14	Selected SCE Hardwire Control Concept	2-12
2-15	Truss Support Requirements	2-12
2-16	Truss Loads	2-13
2-17	Revised Truss Geometry and Configuration	2-13
2-18	SCE Mass Properties	2-14
2-19	Candidate Damping Augmentation Approaches	2-16
2-20	Recommended Damping Approach	2-16
2-21	State Estimator Filter Characteristics	2-18
2-22	Ground Test Program Summary	2-18
2-23	Flight Test Operations Sequence and Timelines for Day 1	2-19
2-24	Construction Operations Test Sequence and Timelines for Day 2	2-19
2-25	Preliminary SCE Program Development Schedule	2-20
2-26	Program Funding Requirements	2-21

LIST OF TABLES

Table		Page
2-1	Primary Requirements for Space Truss Concept Evaluation	2-2
2-2	Results of Numerical Rating Analysis	2-3
2-3	Significant Space Construction Issues and Operational Concerns	2-4
2-4	Selected Construction Operation Tests and Evaluations	2-4
2-5	Selected Structures and Dynamics Experiments	2-4
2-6	Alternative Concept Preliminary ROM Cost Estimates (1981 $)	2-8
2-7	Experiments Concepts Numerical Evaluation	2-8
2-8	Deployable Truss Change Due to Contingency Loads	2-13
2-9	Comparison on Truss Modal Frequencies (Hz)	2-14
2-10	SCE Weight Breakdown	2-14
2-11	Dynamic Testing Summary	2-15
2-12	Variable Damping Ratio Effects on Tip Motion and Stabilization Time	2-15
2-13	Simulation Run Summary for Preliminary 100 m Truss with 100 kg Tip Mass	2-17
2-14	Flexible Payload Comparison	2-17

ACRONYMS AND ABBREVIATIONS

A/D	Analog-to-digital
BIU	Bus interface unit
C&W	Caution and warning
CCTV	Close circuit television
CDR	Critical design review
CER	Cost estimating relationship
CIS	Centaur-in-shuttle
CRT	Cathode-ray tube
CSDL	Charles Stark Draper Laboratory
D&C	Display and control
DAP	Digital autopilot
DIO	Discrete input-output
DIS	Digital integrating system
DOF	Degrees of freedom
DRD	Data requirements document
DRL	Data requirements list
EVA	Extravehicular activity
FSE	Flight support equipment
FSS	Flight support system
GEO	Geostationary earth orbit
GPC	General purpose computer
GSE	Ground support equipment
JSC	Johnson Space Center
KSC	Kennedy Space Center
LEO	Low earth orbit
LSS	Large space system
MDF	Manipulator development facility
MMU	Manned maneuvering unit
MPS	Material processing science
MUX	Multiplexer

NASA	National Aeronautics and Space Administration
OSS	Office of Space Science
OTV	Orbital transfer vehicle
PCM	Pulse code multiplexer
PDR	Preliminary design review
PIDA	Payload installation and deployment aid
PMP	Parts, materials, and processes
PRCS	Primary reaction control system
PROM	Programmable read only memory
PRR	Preliminary requirements review
RCS	Reaction control system
RMS	Remote manipulator system
S/C	Spacecraft
SASP	Science and applications space platform
SBR	Space-based radar
SCE	Space construction experiment
SCEDS	Space construction experiment definition study
SIO	Serial input/output
SOC	Space operations center
VRCS	Vernier reaction control system
WBS	Work breakdown structure

SECTION 1

INTRODUCTION

1.1 SCOPE

This is the first of two volumes comprising the SCEDS Final Report. It contains a summary of all Part I study tasks. Volume II provides detailed study results.

1.2 STUDY OVERVIEW

The top level objectives of the SCEDS program are:

a. To define a basic Shuttle flight experiment which will provide needed data on construction of large space systems from the Orbiter, where it is not practicable to obtain the data from ground tests. This includes experiments in these areas:

   1. Predicted dynamic behavior of a representative large structure.

   2. On-orbit construction operations.

   3. Orbiter control during and after construction.

b. To identify and define evolutionary or supplemental flight experiments for development or augmentation of a basic flight experiment.

The study activities were divided into six major tasks with appropriate subtasks within the major task headings as shown in Figure 1-1. In Task 1 candidates for deployable structures, the basic experiment, EVA/RMS operations, and suitcase experiments were defined and evaluated; a damping augmentation approach was selected; and the effects of restowage and return of the experiment were identified. Task 1 resulted in the selection of experiments and concepts by the joint NASA/JSC, Draper Lab, Convair working team. The selected concepts, tests, experiments, and operations were then used to prepare a preliminary design and and analysis. These data were used to derive mass properties and dynamic characteristics for analysis by Draper Lab. A preliminary test plan and a program plan were then prepared.

1.3 SUMMARY

The preliminary design for a basic Space Construction Experiments (SCE) and concepts for additional suitcase experiments for Extra-vehicular Activity (EVA) and Remote Manipulator System (RMS) construction operation were developed to incorporate the following characteristics:

a. Share a Shuttle mission with other payloads as a payload of opportunity.

b. Remain attached to the orbiter throughout test. Jettison capability is provided; however, the experiment will normally be restowed and returned to earth by the orbiter.

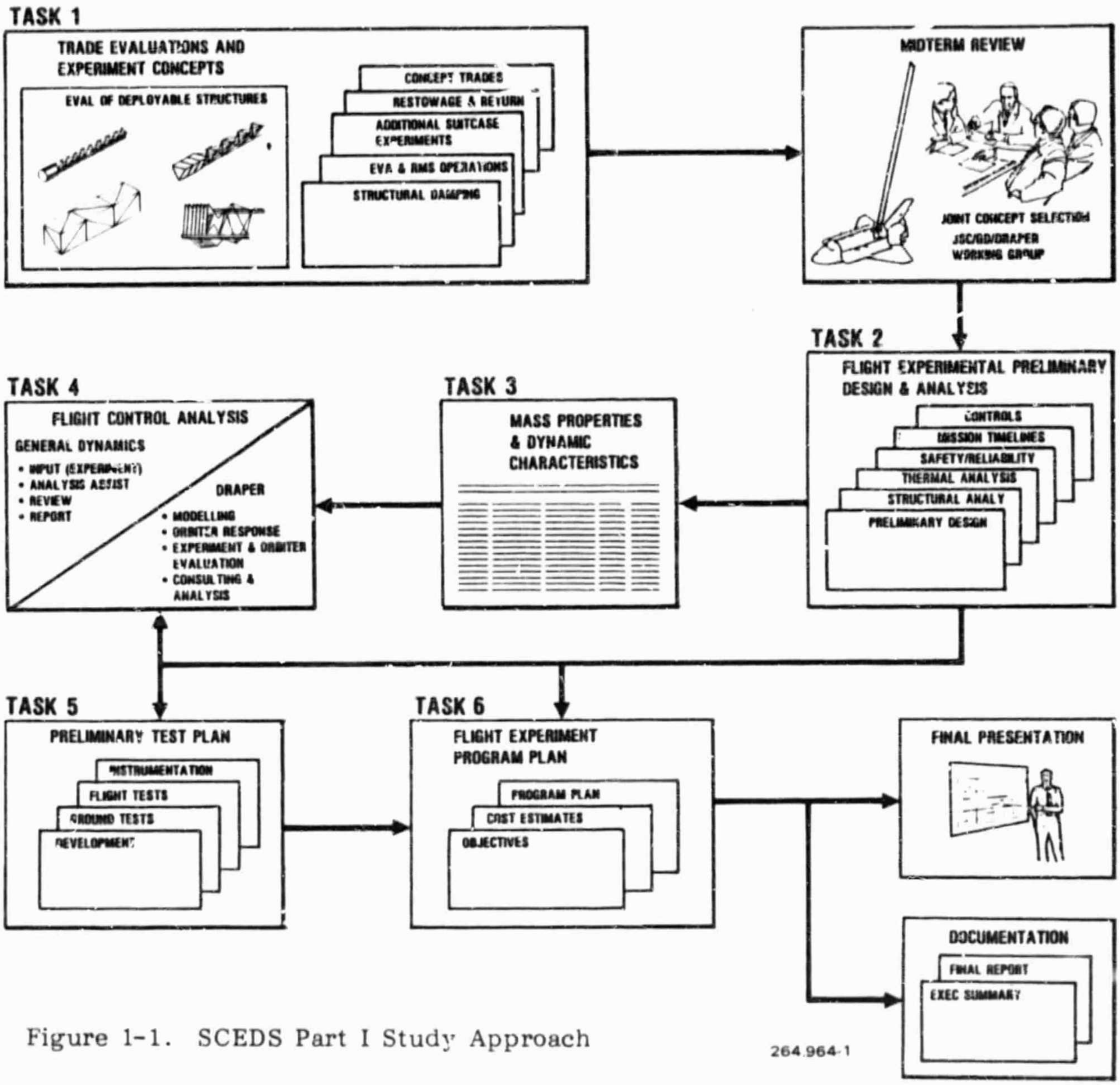


Figure 1-1. SCEDS Part I Study Approach

c. Exercise a variety of appropriate Large Space System (LSS) construction and assembly operations utilizing basic Space Transportation System (STS) capabilities (EVA, RMS, CCTV, Illumination, etc.) to be correlated with ground tests and simulations.

d. Use representative LSS elements. The basic experiment employs a deployable low natural frequency structure. The structure will have a very low coefficient of thermal expansion achievable through the use of graphite composite materials of construction. Structural dynamic tests will provide data to be correlated with math and ground test models.

e. Provide options to approach proven capabilities of the orbiter conservatively and safety exceed proven limits to establish usable capabilities for control, mission timelines, and critical interfaces. These options include variability of mass moment of inertia and variable damping augmentation.

ORIGINAL PAGE IS
OF POOR QUALITY

SECTION 2

STUDY RESULTS

Study results are summarized in the following subsections. These include selection of the structure, selected construction operations experiments, preliminary design and analysis, test plans, and programmatics.

2.1 STRUCTURE

2.1.1 DEPLOYABLE STRUCTURES REQUIREMENTS. Large Space Systems such as the Space Operations Center (SOC), Geostationary Platform (Geoplatform), Science and Applications Space Platform (SASP), and Space-based Radar (SBR) (Figure 2-1) are being defined today for potential implementation in the near future. In defining requirements for the SCE, these are the primary applications to consider, if SCE is to be a cornerstone of early space construction efforts. Each concept represents an integrated modular construction approach, whereby basic system elements such as reflectors, feed modules, habitability modules, and power modules are interconnected through a primary structural element, usually depicted as a deployable truss. A single deployable truss element could be developed to meet the needs of these and other future space platforms. Use of such an element in the SCE will assure an applicable data base for LSS design and bring the technology for LSS structures to a high initial state of readiness. A review of selected LSS concepts revealed requirements which were used to evaluate space truss candidates. Table 2-1 summarizes these requirements and indicates which have major importance to the systems considered.

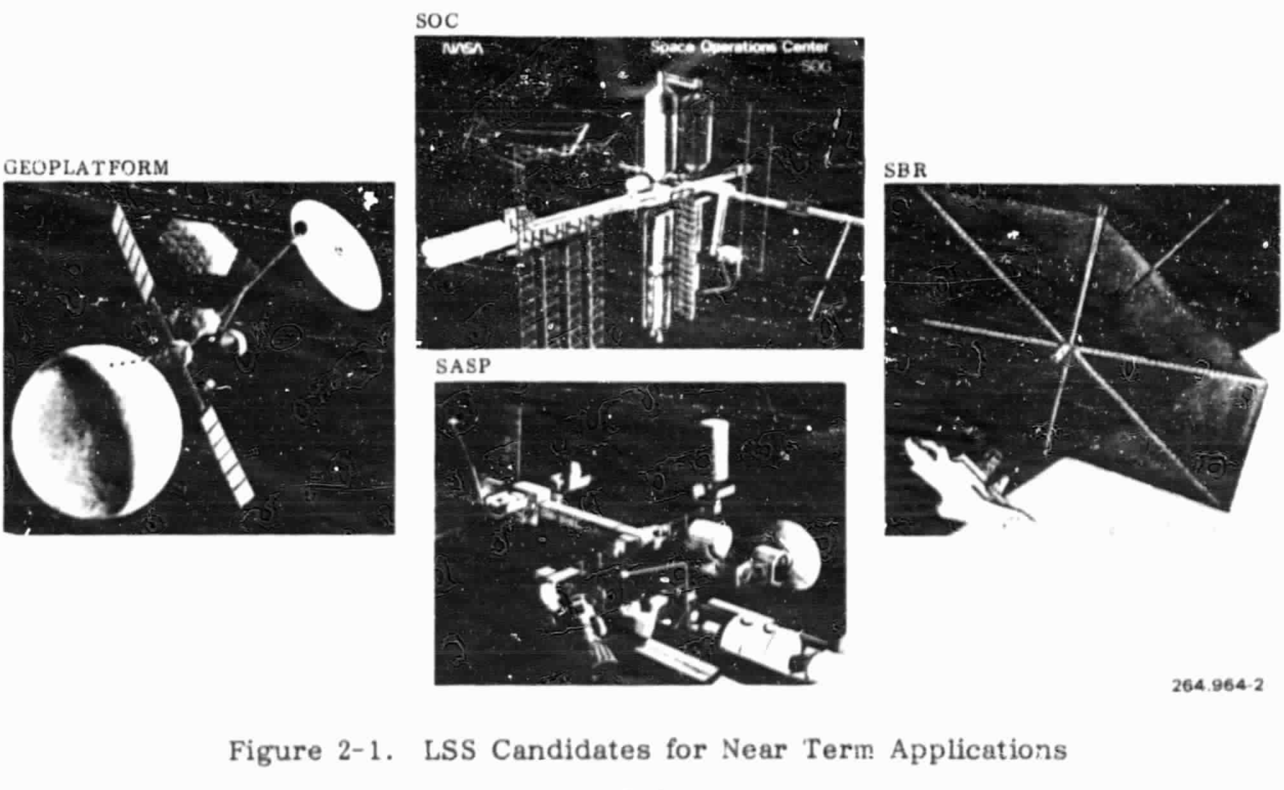


Figure 2-1. LSS Candidates for Near Term Applications

Table 2-1. Primary Requirements for Space Truss Concept Evaluation

Deployable Space Structure Requirements	Application: Space operations center	Geostationary platform	Science applications platform	Space radar system	Space construction experiment
Physical characteristics					
• Strength		✓		✓	✓
• Stiffness	✓	✓	✓	✓	✓
• Column stability		✓		✓	
• Thermal stability		✓	✓	✓	
• Structural efficiency (lightweight)		✓		✓	
• Orbital life expectancy		✓		✓	
Stowage & deployment factors					
• Packagability		✓		✓	✓
• Controlled deployment		✓	✓	✓	✓
• Retraction capability				✓	✓
System compatibility factors					
• Suitability as modules for space assembly	✓	✓	✓		✓
• Suitable for hard mounting of substructures & equipment modules	✓	✓	✓	✓	✓
• Compatible with preinstalled hardware & service lines	✓	✓	✓	✓	✓
• Manned traverse capability	✓		✓		✓
Other factors					
• Cost effectiveness					✓
• Reliability (mech & struc)	✓	✓	✓	✓	✓
• Hardware development status					✓
• Applicability to LSS					✓

264.964-28

2.1.2 DEPLOYABLE STRUCTURES EVALUATION AND SELECTION. A review of available data on deployable structures and LSS technology plus Convair's in-house activities in the design and development of space structures led to selection of ten LSS structural beam candidates to be evaluated for applicability to the SCE. These candidates are shown in Figure 2-2, including the common basis used for comparison.

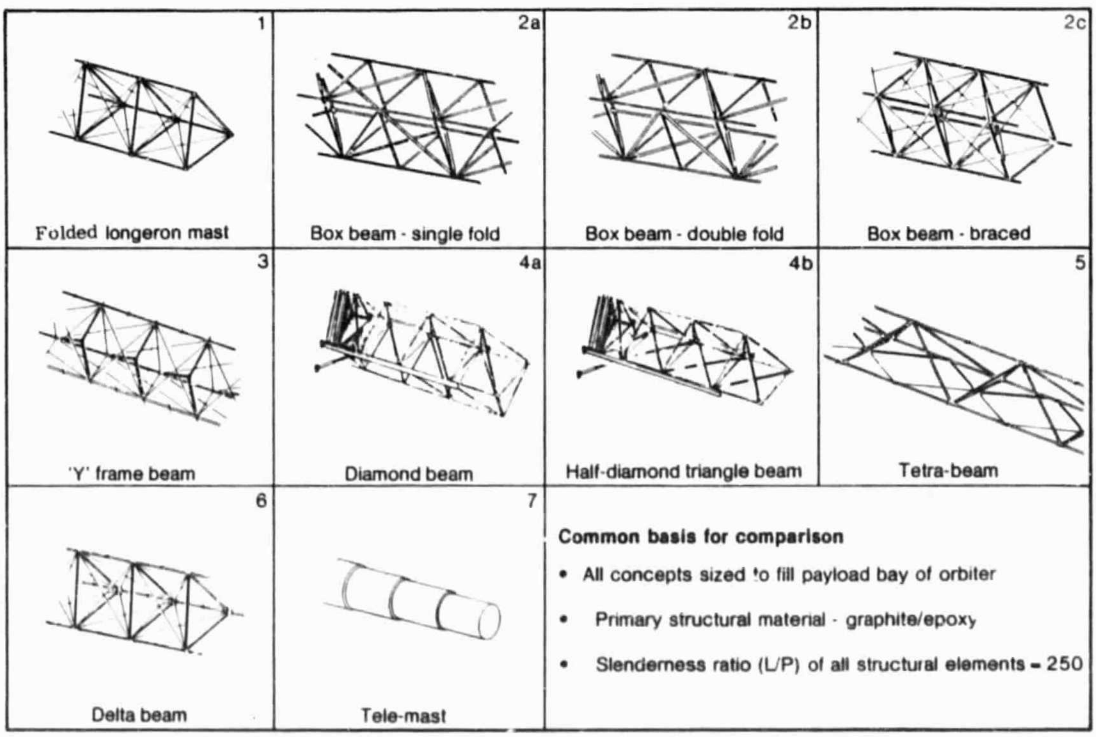


Figure 2-2. Candidate Deployable Structure Concepts

Each of the candidate structures was assessed numerically, using rating factors and weighting factors with respect to each requirement in Table 2-1.

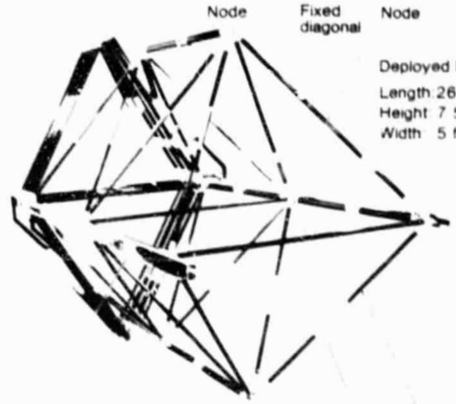
Table 2-2. Results of Numerical Rating Analysis

Rankings

Evaluation criteria	Concept									
	1	2a	2b	2c	3	4a	4b	5	6	
Physical characteristics	10	3	4	7	9	2	6	5	8	1
Stowage & deployment	[illegible]	10	6	8	4	2	1	7	9	5
LSS compatibility	7	4	4	4	6	1	2	5	3	8
Other factors	7	9	3	4	8	1	2	6	10	5
Overall ranking	9	6	3	7	8	1	2	5	10	4

264.964-29

The sums of the products of rating and weighting factors resulted in the relative rankings shown in Table 2-2. This evaluation shows tetrahedral diamond cross-section beam (Figure 2-3) to have the best overall ranking. The half diamond triangle beam, with the second best overall rating, offers a lower cost alternative, but with reduced reliability and less than optimal physical characteristics. Concept 4a was carried into the flight experiment concept development phase along with the Concept 4b, as they can be used interchangeably.



264.964-4

Figure 2-3. General Dynamics Prototype Deployable Truss

2.2 CONSTRUCTION OPERATIONS

2.2.1 CONSTRUCTION OPERATIONS ANALYSIS. An analysis was performed to identify and define significant LSS construction issues and operations concerns (Table 2-3) that needed to be considered for incorporation in the SCE. These issues and concerns were then used to derive EVA and RMS operations as well as additional suitcase experiment concepts. A concept for restowage and return of the SCE was also developed.

2.2.2 IDENTIFICATION OF TESTS AND EXPERIMENTS. Identification and evaluation of candidate tests and experiments led to selection of the operations, tests, and evaluations summarized in Tables 2-4 and 2-5. These recommended experiments fall in four major categories. Items in the category of "later flight experiments" are considered unavailable for early flight test due to current development plans.

All experiments can be performed as part of the basic flight experiment. Those having suitcase applicability require additional hardware.

Table 2-3. Significant Space Construction Issues and Operational Concerns

NO.	DESCRIPTION
1.	Packaging, stowage and support techniques for deployable structures and systems equipment in the Orbiter cargo bay.
2.	Pre-deployment preparations and operations.
3.	Handling, control, and disposition of jigs, fixtures, tracks, and accessories required to deploy and retract structures.
4.	Control of structural deployment and retraction.
5.	In-process quality verification and condition monitoring.
6.	Checkout, maintenance, repair, contingency procedures, and equipment.
7.	Attachment/joining of major structural elements and subsystem modules.
8.	Installation of subsystem equipment before, during, and after deployment of structure.
9.	Combined EVA/RMS installation and assembly capabilities and techniques.
10.	Applications and effectiveness of special RMS end effectors for grasping, holding, manipulating, and torquing.
11.	Effectiveness of illumination/visibility visual aids.
12.	Separation and release of structure from Orbiter.
13.	Reattachment or berthing of structure to Orbiter.
14.	Handling and positioning of structure.
15.	Restowage of deployable structures and equipment in Orbiter cargo bay.
16.	Orbiter induced dynamic effects on structure, deployment, construction equipment, and operations.
17.	Correlation of predicted structural dynamic modes and loads with measured characteristics.
18.	Inherent structural damping characteristics and active damping techniques and equipment.
19.	Structural rattle and backlash effects.
20.	Structural thermal effects.
21.	Structural inertia and vibration effects on Orbiter control capabilities and performance.

Table 2-4. Selected Construction Operation Tests and Evaluations

Early Flight Experiments	Operations Tests & Evaluations	Applicability	
		Basic	Suitcase
RMS/standard end effector	Deploy & retract truss	•	
	Pickups & handoffs (special end piece)	•	•
	Position & attach modules	•	•
	Surveillance & inspection	•	
	Engage/maneuver/position truss	•	•
	Assess illumination/visibility	•	
EVA	Install structural elements/rigging	•	•
	Install subsystem elements	•	•
	Assess joints, couplings, connectors	•	•
	Repair/maintenance operations	•	
	Assess portable work aids/fixtures	•	•
	Assess illumination/visibility	•	
	Assess RMS effectiveness	•	•
	Inspection/verification/checkout	•	
Later flight experiment candidates	Birthing latch interface mechanism	•	•
	RMS special end effectors	•	•
	Handling & Positioning aid	•	•
	Open cherry picker	•	•
	MMU	•	•

264.964-30

Table 2-5. Selected Structures and Dynamics Experiments

Early Flight Experiments	Operations Tests & Evaluations	Applicability	
		Basic	Suitcase
Structures & dynamics	Assess deployment/retraction techniques	•	
	Assess prewiring/harnessing/conduits	•	
	Assess hardware preinstallation techniques	•	
	Interactions with EVA/RMS	•	
	Instrumentation techniques	•	
	Rattle & backlash effects	•	
	Thermal control/stability techniques	•	
	Damping techniques	•	
	Modal measurements	•	
	Interaction with orbiter DAP	•	
	Orbiter maneuvering effects	•	
	Structural joining techniques	•	
	Structural performance/behavior	•	
	– Attached to orbiter	•	
	– Free-free mode (optional)	•	

264.964-31

Use of the RMS to perform the predeployment sequence (Figure 2-4) was evaluated as a means of simplifying drives and controls for the SCE. Concepts for attaching a drive socket wrench to a standard grapple fitting included use of the Universal Service Tool (UST). Other provisions for RMS usage were a special end piece for pickups and handoffs, and attachment of a standard grapple fitting to the truss for handling and maneuvering a segment of structure.

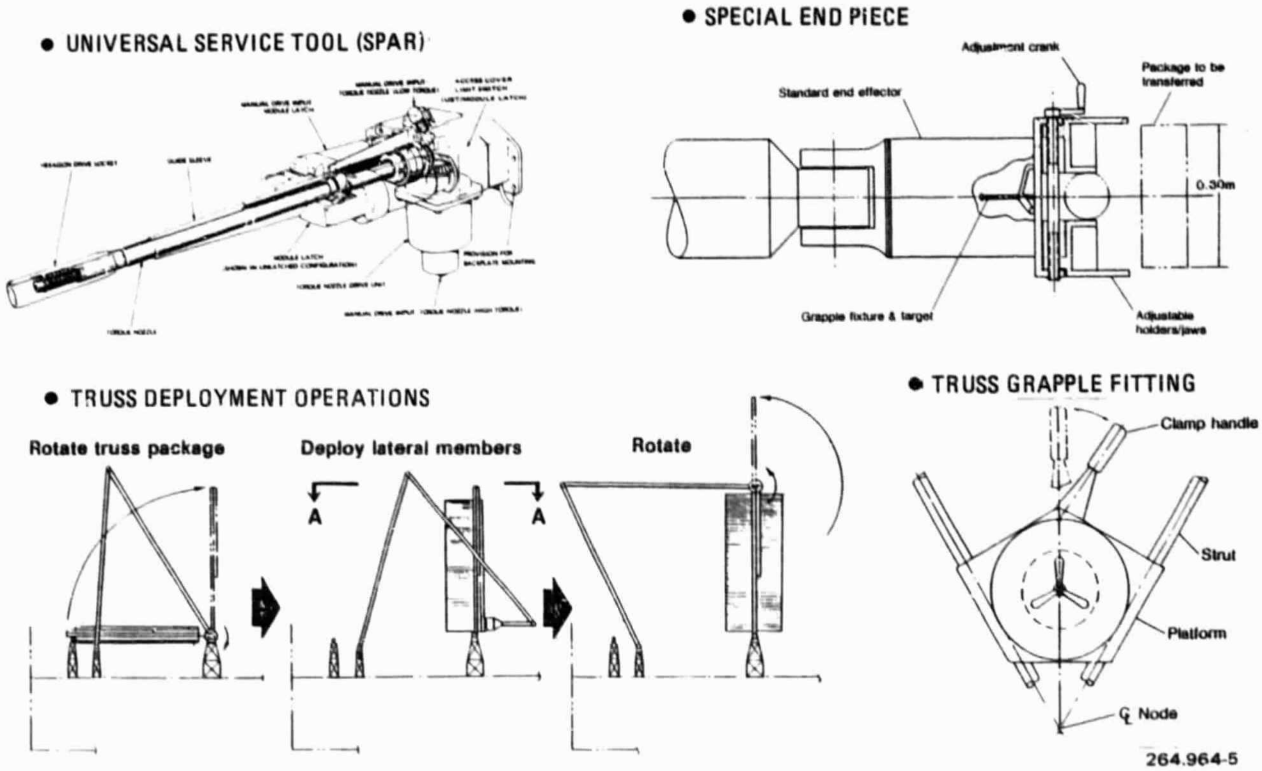


Figure 2-4. RMS Deploy/Retract Operations and Suitcase Experimental Hardware

Construction of major space platforms will require the capability to install subsystems equipment before, during, and after deployment of the structure. Preinstallation of conduits (Figure 2-5) and interface mechanisms will minimize on-orbit assembly. However, high density packaging of structure precludes large module preinstallation.

Concepts for EVA/RMS experiments for subsystem hardware installation were defined as shown in Figures 2-6 and 2-7. Universal attachment modules provide a means of attaching both man and equipment to the structure. The structure incorporates NASA-developed quick-connect joints for attachment of superstructures to the truss.

ORIGINAL PAGE IS
OF POOR QUALITY

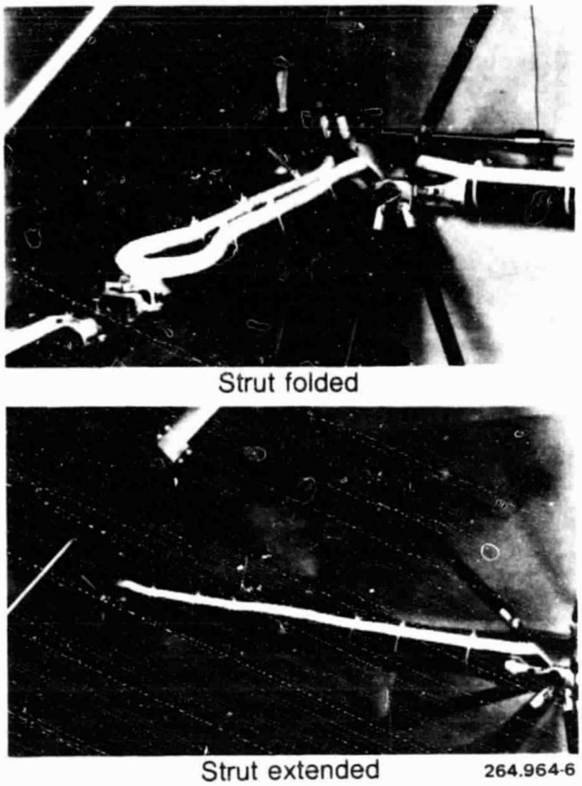


Figure 2-5. Preinstalled Cc..duit Demonstration

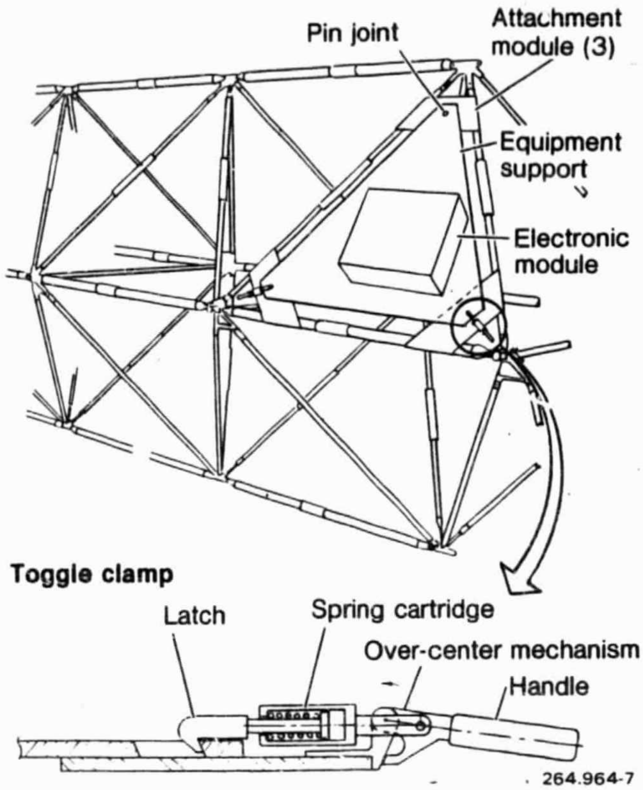


Figure 2-6. Subsystem Module Installation Concept

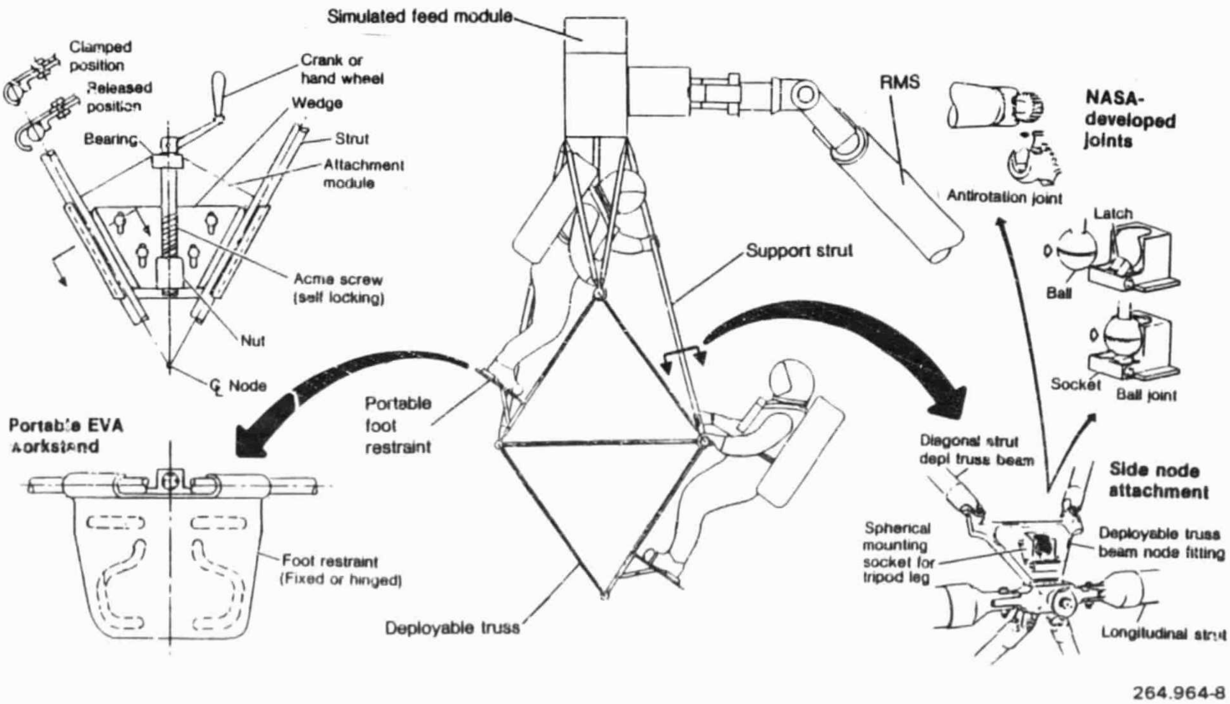


Figure 2-7. EVA/RMS Construction Operations Test Concept

2.2.3 EVOLUTIONARY OPTIONS. The selected experiments suggest an evolutionary approach with as many as five options for accomplishing those and future experiments (Figure 2-8).

a. Option 1 would limit the flight experiment to EVA and RMS experiments. A short segment of deployable structure such as the one shown in Figure 2-3 could be used to facilitate installation and assembly tests at minimum development cost.

b. Option 2 would be to perform the structures and dynamics tests and RMS tests and evaluations with no EVA, using a long, instrumented, and damper-equipped deployable truss.

c. Option 3, which is the preferred option for the SCE, would be to conduct all of the EVA/RMS and structures and dynamics tests in a single mission.

d. Option 4 performs all recommended tests and evaluations including a free-free mode structural dynamics test, by separation of the structure for free-flight.

e. Option 5 is a spinoff benefit of developing the SCE. Reuse of the SCE hardware will provide the capability to test a variety of LSS subsystems, either attached to the Orbiter or as free-flight experiments.

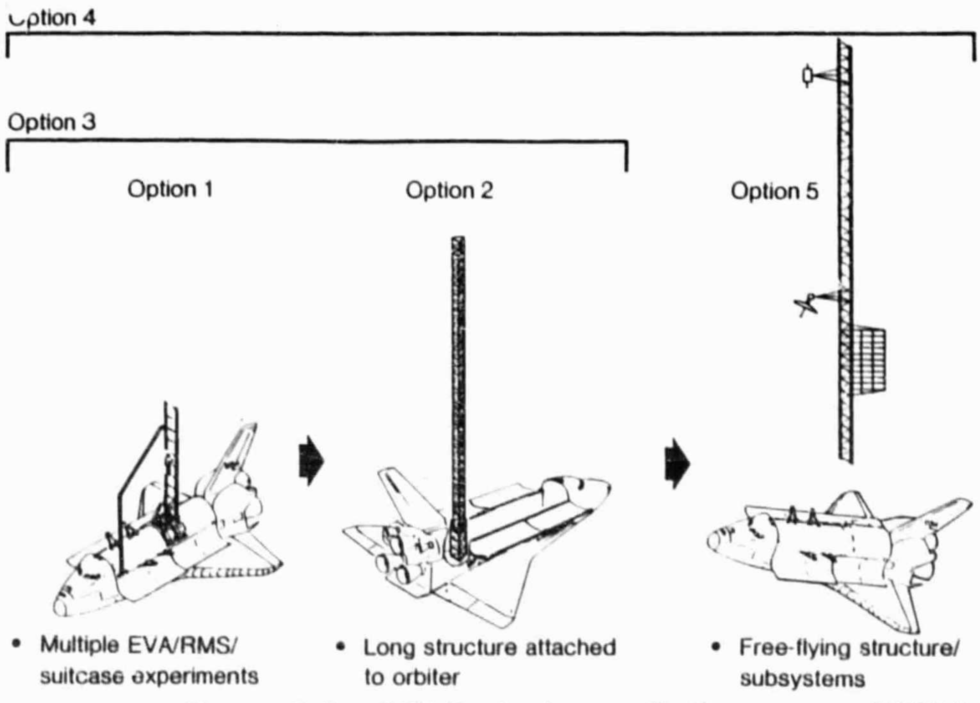


Figure 2-8. SCE Evolutionary Options

2.3 CONCEPT SELECTION AND PRELIMINARY DESIGN

2.3.1 STS FLIGHT CANDIDATES EVALUATION. The STS Flight Assignment Baseline per JSC 13000-5 was analyzed to identify potential flight opportunities for the SCE. Although these data were preliminary and have since undergone major revision, they provided good insight into the limitations and constraints of the types of missions that need to be considered.

The evaluation indicated that missions involving satellite deployment only and satellite deployment plus Material Processing Science (MPS) pallets provide the fewest constraints to incorporation and operation of the SCE.

2.3.2 EXPERIMENT CONCEPTS AND EVALUATIONS. Seven SCE concepts were developed and evaluated (Figure 2-9). Candidate STS flight configurations were used to determine space and envelope constraints. Two concepts were defined for use with the Spacelab 6 mission even though the evaluation indicated it to be a poor candidate. This was done to provide more contrast between competing concepts and to illustrate a wider range of options than is seemingly available.

Evaluations of the alternative SCE concepts included timeline comparisons, Orbiter compatibility evaluations (visibility, RMS, illumination, etc.) and preliminary ROM cost comparisons. (See Table 2-6.) Alternative experiment control concepts were also evaluated.

The numerical evaluation of the alternative concepts is presented in Table 2-7. The sum of the rating factors shows highest potential benefits for concepts 1 and 2A. Concepts 2, 3, 4, and 5 were eliminated because they have the least potential benefits. Concept 2B exceeds the $10M program cost guideline. Concept 2A was selected because of its superior overall capabilities and high cost effectiveness ratio.

Table 2-6. Alternative Concept Preliminary ROM Cost Estimates (1981 $M)

Concept	Development cost	Unit cost	Total
1	5.5	1.2	6.7
1-1*	5.1	1.0	6.1
2	4.5	1.4	5.9
2A	6.5	1.6	8.1
2B	11.2	2.7	13.9
3	4.8	1.5	6.3
4	3.2	0.8	4.0
5	5.5	1.7	7.2

*Triangular vs diamond beam reduces cost by an average of 15%

264.964-32

Table 2-7. Experiments Concepts Numerical Evaluation (Scale of 1-5, High Numbers Best)

Evaluation Criteria	Experiment Concepts						
	1	2	2A	2B	3	4	5
Performance capabilities							
• CAP effects testing	3	5	5	5	5	2	5
• Structural dynamics testing	3	4	4	5	5	2	5
• RMS operations	5	2	3	5	2	1	3
• EVA operations	5	0	5	5	0	0	3
• Deployment/retraction	4	4	4	3	4	2	5
• Suitcase experiments	5	0	5	3	0	0	2
Program & operational							
• More flight opportunities	5	4	4	4	1	5	1
• Orbiter compatibility	3	4	4	4	4	2	5
• Potential for multi-mission options	3	4	5	2	4	1	4
• Minimal development risk	4	4	4	2	4	5	4
$\sum$ Rating factors	40	31	45	38	29	20	37
Benefits/$M cost* ratio	5.97	5.25	5.56	2.73	4.60	5.00	5.14

*Shuttle user charges not included

264.964-33

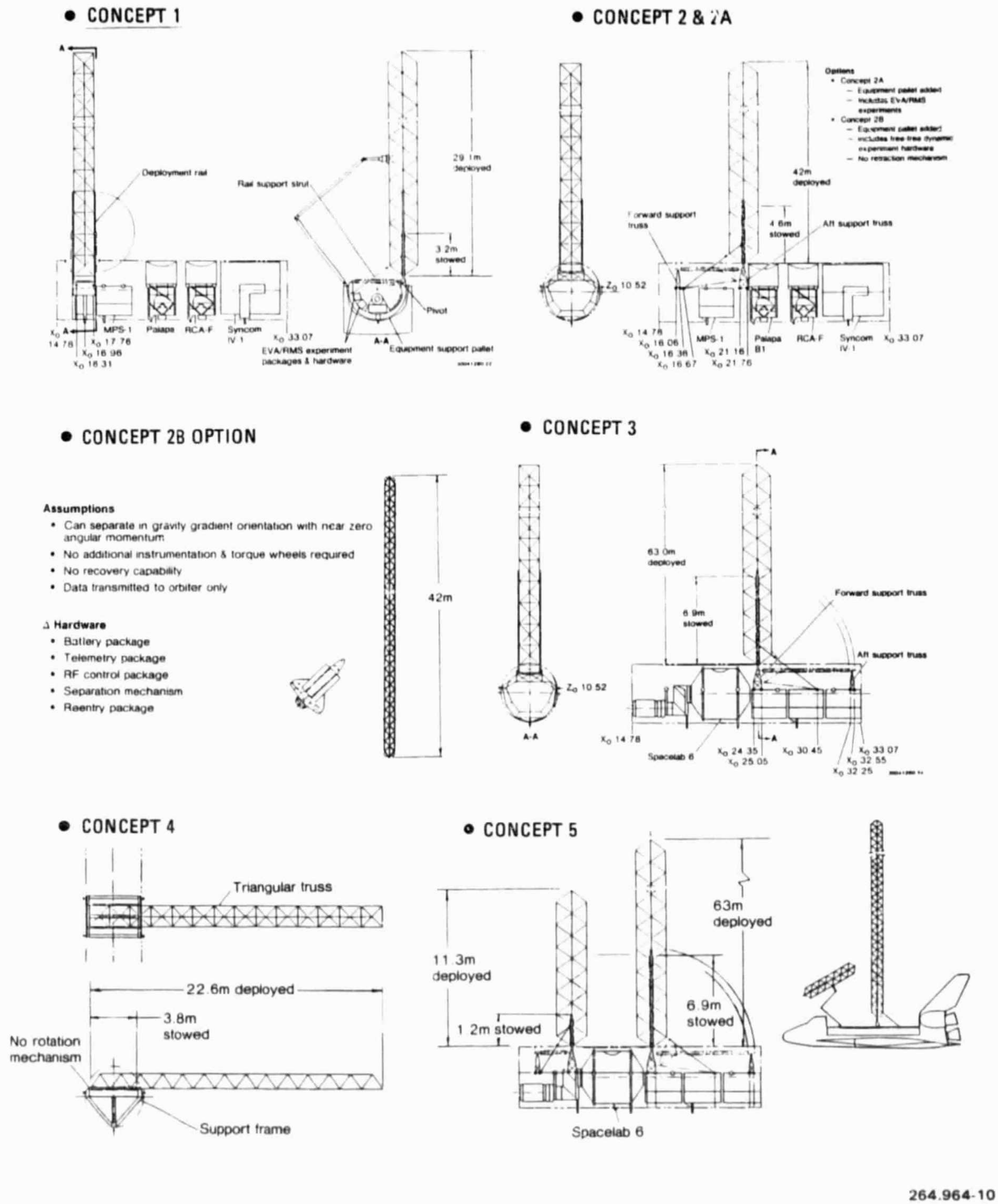


Figure 2-9. Alternative SCE Concepts

2.3.3 PRELIMINARY DESIGN. The preceding trades and concept evaluations resulted in the selection of a deployable tetrahedral truss supported in the Orbiter by a support structure (Figure 2-10). The baseline configuration assumes an arrangement whereby the basic experiment shares space in the forward section of the payload bay with an MPS experimental pallet on a flight accompanied by deployed satellite payloads. Additional suitcase experiments for EVA/RMS experiments are integrated into the SCE payload within the equipment stowage envelope.

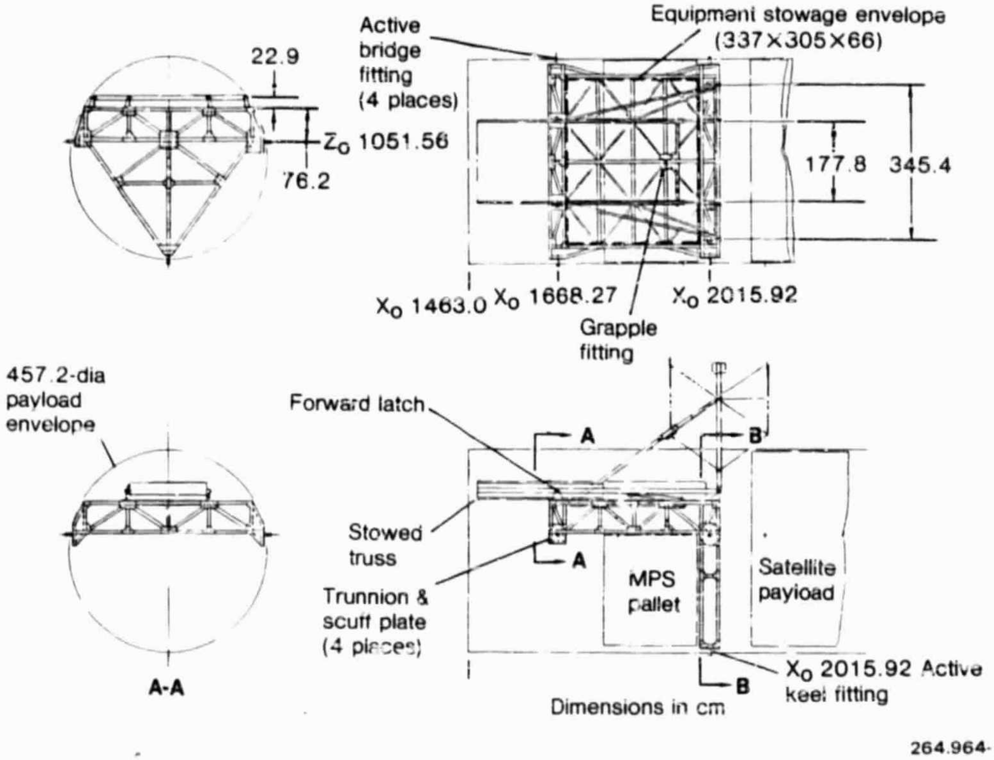
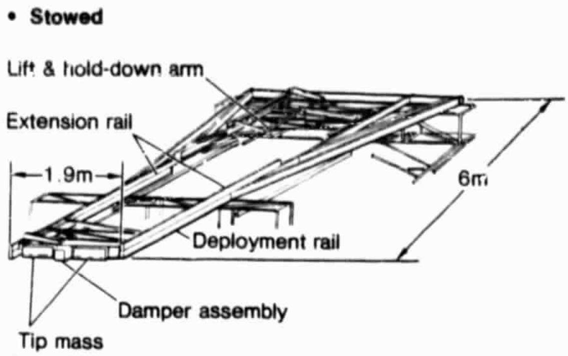
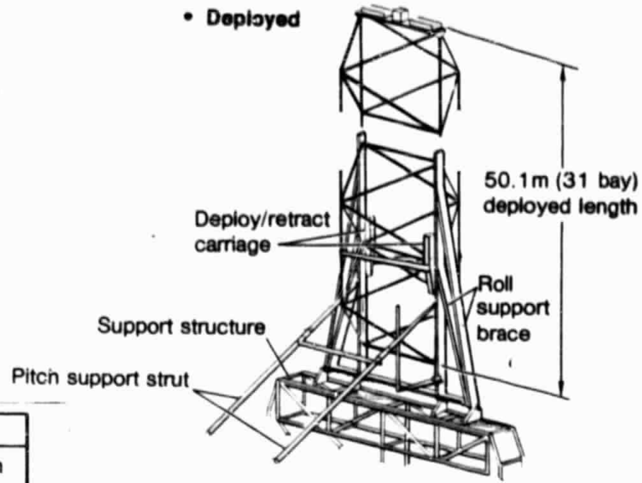


Figure 2-10. SCE Support Structure and Stowage Envelope

The 50.1m truss is stowed in its deployment rail in a short flat packaging envelope (Figure 2-11). The initial deployment sequence is performed with the RMS. Special bell-mouthed fittings are provided for hex hand-drive insertion to permit unlatching and rotation functions to be driven by the UST or RMS wrist (Figure 2-12). The opposite sequence is used for restowage.

Two truss deployment/retraction carriages (Figure 2-13) automatically perform the functions necessary for controlled deployment and retraction of the truss. During deployment, each drive latch engages a roller guided node fitting on opposite sides of the rail. The carriages drive in the deploy direction until a truss bay is open and locked. The drive latches are disengaged and the carriages return to pickup the next bay node fitting. During retraction, two hinge trippers on each carriage unlock the hinges in one bay so the bay will collapse by the action of the carriages.





• **Performance characteristics**

Item	Value
Deployment/retraction rate	3 bays/min
Deploy/retract drive speed	0.3m/sec
Power (peak)	500w
Damping ratio (active)	0, 1%, 2%
Tip mass	400 kg

264.964-12

Figure 2-11. Basic Experiment General Arrangement and Characteristics

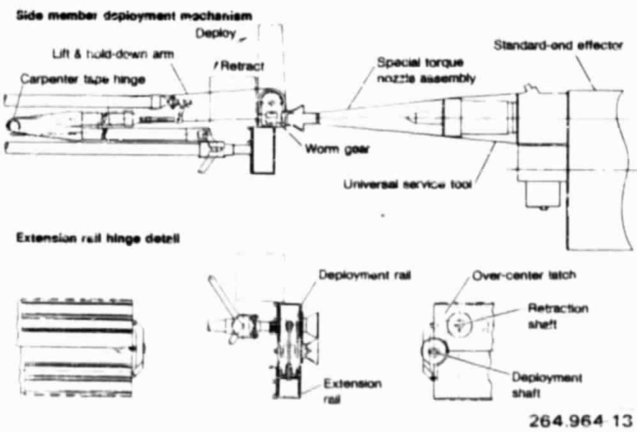


Figure 2-12. RMS Driven Deployment Mechanisms

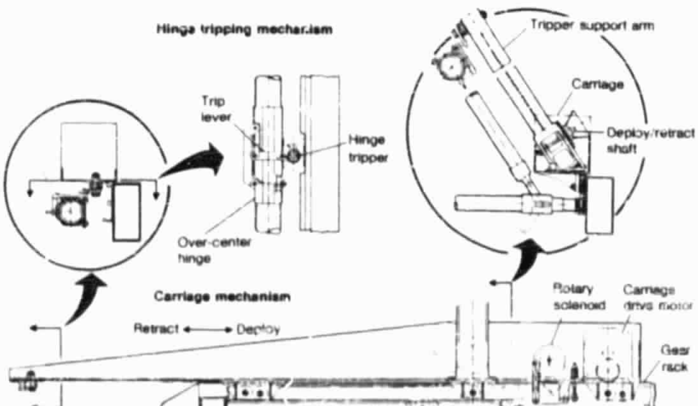


Figure 2-13. Deployment/Retraction Carriage Mechanisms

The selected approach for the SCE control shown in Figure 2-14 uses a microprocessor controller, the Shuttle-qualified CIS Control Unit with a Z80, 8-bit processor. For instrumentation, a standard off-the-shelf PCM Encoder provides a 16 Kbps data stream to the Orbiter payload data interleaver for recording purposes. Hard-wire interfaces are utilized between the deployable truss and support structure, and the Payload Specialist Station.

The Payload Specialist can command or monitor any function performed by the Control Unit via a computer keyboard and display on the operator's panel. Continuous readouts are provided to indicate the extent of truss deflections and the progress of deployment or retraction. In case of emergency, the arm/safe switch can be operated for truss jettison.

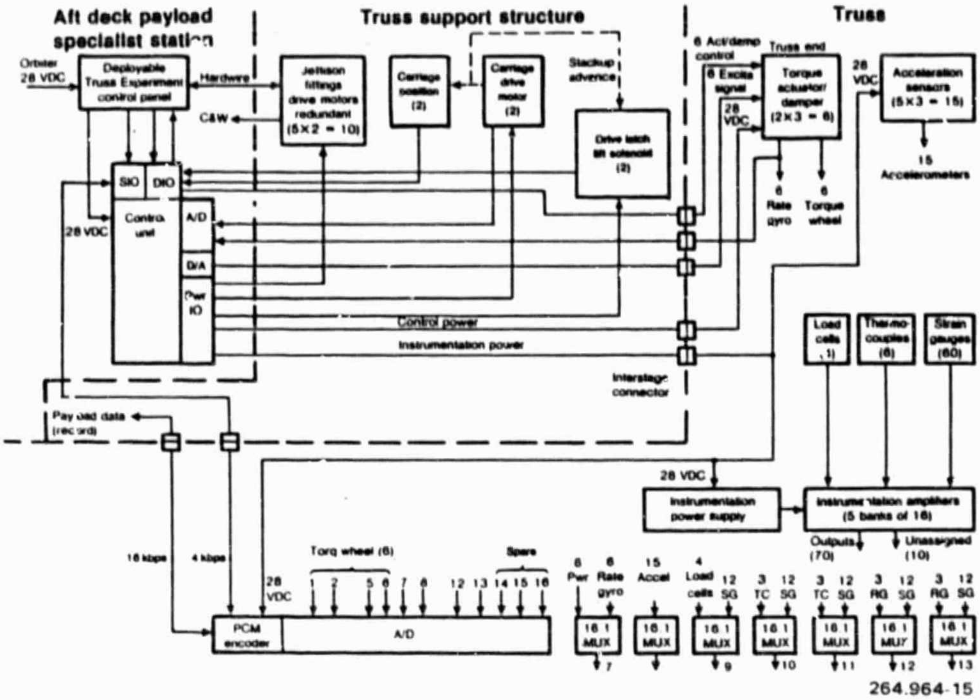


Figure 2-14. Selected SCE Hardwire Control Concept

2.4 ANALYSIS

2.4.1 STRUCTURAL ANALYSIS. The Convair prototype deployable truss (Figure 2-3) was configured to the size and strength requirements established by a previous LSS study of a large radar array. This configuration was used as the baseline structure for the SCE. The impacts of SCE operations on the baseline structural configuration were determined.

Primary reaction control system (PRCS) thruster firings are considered worst-case contingency loads because they would normally not be used during space construction operations. However, during attitude control and maneuvering activities with the vernier RCS (VRCS), failure of a vernier jet to shutoff may cause PRCS firings to occur.

The preliminary design loads were derived as quasi-static responses to PRCS firings. The steady-state responses caused by PRCS pitch and roll maneuvers were multiplied by a dynamic amplification factor of 2 for conservative estimates.

The stress analysis resulted in the truss support arrangement shown in Figure 2-15.

The deployment rails are braced to react pitch and roll moments for contingency loads to ensure the safety of the crew

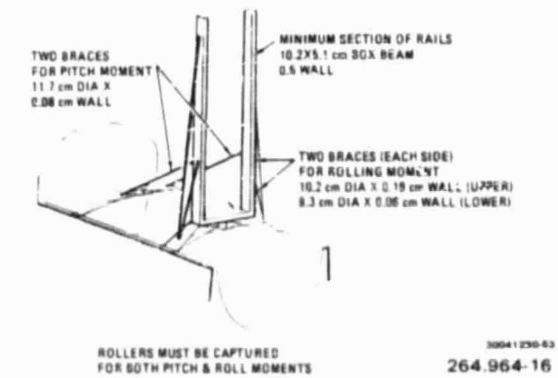


Figure 2-15. Truss Support Requirements

and Orbiter. The pitch braces also serve as handholds for EVA in the vicinity of the support structure.

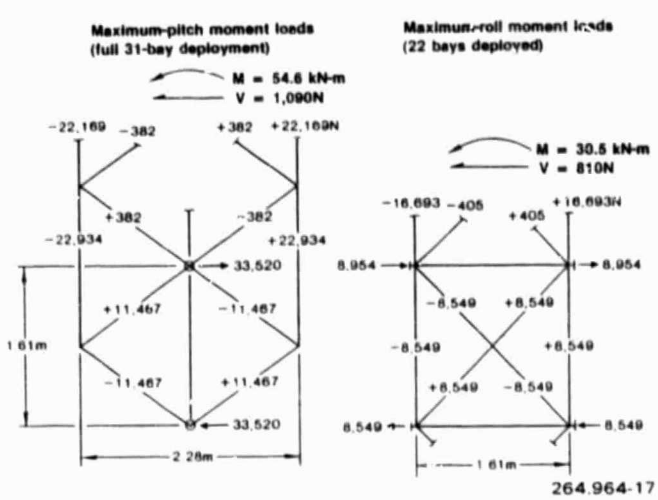


Figure 2-16. Truss Loads

The worst-case truss member loads are shown in Figure 2-16. The magnitude of these loads had a number of undesirable effects on the baseline truss geometry and configurations summarized in Table 2-8 and Figure 2-17. These physical changes increase weight, packaging size, and cost. They also increase the stiffness of the truss, which increases the modal frequencies. This detracts from the capability to perform DAP interactions testing as discussed in Section 2.5.3.

Table 2-8. Deployable Truss Change Due to Contingency Loads

Item	Baseline	Change
Longitudinal Tube Diameter	4.50 cm	Same
Longitudinal Tube Wall Thickness	0.08 cm	0.13 cm
Diagonal Tube Diameter	2.54 cm	3.18 cm
Diagonal Tube Wall Thickness	0.08 cm	0.30 cm
1 Bay Packaged Length	17.42 cm	18.44 cm
Packaged Height	20.47 cm	23.67 cm
Diagonal Member Hinges	Carpenter Tape	Over-Center Locking

264.964-24

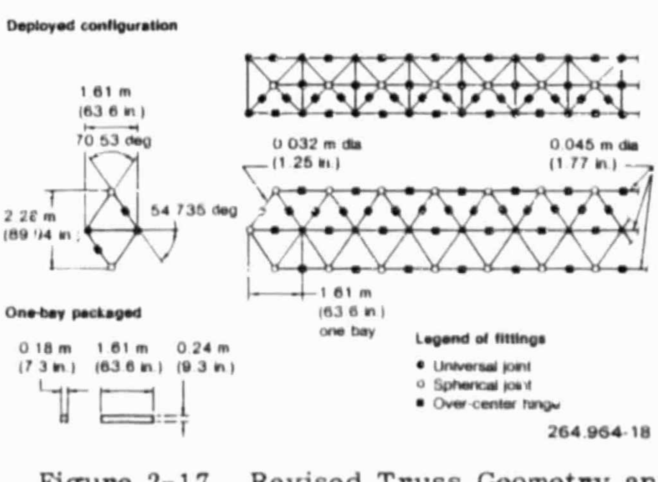


Figure 2-17. Revised Truss Geometry and Configuration

The modal frequencies of the truss are presented in Table 2-9. The first configuration assumes the truss and support rails are rigidly mounted to a rigid Orbiter. The "soft mounted" configuration includes additional flexibility in roll between the truss and the Orbiter with a spring value of 1.0×10^5 N-m/rad. This additional roll flexibility reduces the first roll bending modal frequency to less than 0.05 Hz. It will also attenuate truss loads.

The answer to the truss loads problem will require further analysis using flexible mounting in the Draper Lab's DAP simulations. Once a mounting flexibility is selected and the size of the tip mass is validated, the structure can be sized for optimum cost and performance.

2.4.2 MASS PROPERTIES. The mass properties computed for the SCE are presented in Figure 2-18 and the weight breakdown in shown in Table 2-10.

The tip mass accounts for the wide separation of the center of mass from the Orbiter. Use of the RMS to jettison the SCE while deployed could create unacceptable moments on the RMS unless all RCS activity is disabled. A system to jettison the tip mass may be required.

Table 2-9. Comparison of Truss Modal Frequencies (Hz)

Mode	Rigid Mount	Soft Mount
1	0.200	0.046
2	0.237	0.237
3	2.96	2.00
4	3.67	3.67
5	8.71	7.34
6	10.15	9.24
7	11.94	11.94
8	18.54	15.62

Truss Characteristics

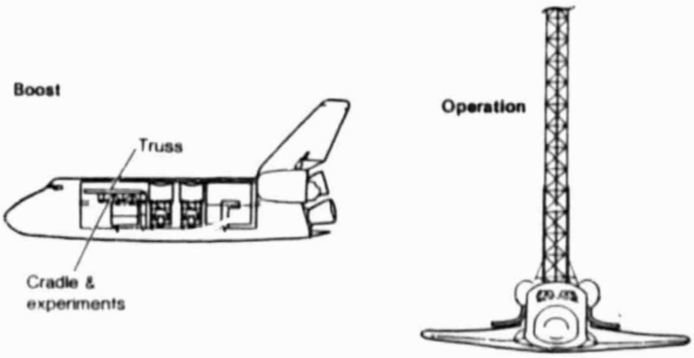
Length	50 meters
Tip Mass	400 kilograms
Stiffness (EI)	6.088×10^7 N-m^2 (pitch)
	2.936×10^7 N-m^2 (yaw)

264.964-35

Table 2-10. SCE Weight Breakdown

Item	Weight lb	Weight kg
Cradle	762	346
Truss	354	161
Deployment Structure	222	101
Deployment Mechanisms	156	71
Truss Equipment	955	433
Miscellaneous Electrical	35	16
Suitcase Experiments	200	91
TOTAL	2,684	1,219

264.964-36



Deployed phase	Center of mass (in.) X	Y	Z	Moment of inertia (kgm^2) I_{xx} (Roll)	I_{yy} (Pitch)	I_{zz} (Yaw)
1/3	775	0	666	8.11×10^4	8.21×10^4	2.53×10^3
2/3	775	0	958	3.03×10^5	3.04×10^5	2.53×10^3
Full	775	0	1,257	6.47×10^5	6.49×10^5	2.53×10^3

264.964-19

Figure 2-18. SCE Mass Properties

2.4.3 THERMODYNAMIC CONSIDERATIONS. The issue of thermal deflections of the deployable truss is considered to be of minor importance provided the structural members are very low CTE composite materials. GY-70/930 graphite-epoxy material is recommended for extensive use both for tubes and fittings. This will provide the best joint compatibility, minimize fitting manufacturing costs, and achieve a near-zero CTE structure. Ground testing of truss struts and fittings CTE and heat transfer characteristics are considered sufficient to accurately predict deflections. Specific meansurement of thermal deflection in space is not planned as these deflections will not be significant enough to warrant the added cost of measuring. Similarly, temperature measurements of the truss members would provide little useful data.

2.5 FLIGHT CONTROL ANALYSIS

2.5.1 DYNAMIC TESTING. Structural and control dynamics tests were selected to evaluate key issues as identified in Table 2-11. The first test has been limited to roll maneuvers since that axis, with its smaller moment of inertia, is influenced

more by flexible structure than either pitch or yaw. Random noise modal surveys have been chosen since they are significantly more efficient time-wise than other techniques. However, one sinusoidal excitation and free decay test has been included to provide data on amplitude sensitive behavior.

Table 2-11. Dynamic Testing Summary

Issues

1. Effect of test structure flexibility & vibration on orbiter & DAP
2. Effect of orbiter-induced dynamics on test structure
3. Minimum modal damping ratios
4. Dynamic modeling accuracy, especially for higher modes

Tests

Tests	Issues 1	2	3	4
Small roll maneuvers at partial & full deployment — decreasing damping augmentation at each test length	✓	✓		
Random noise excitation modal surveys	✓		✓	✓
Sinusoidal excitation & free decay of higher mo	✓		✓	✓

Instrumentation & excitation

- Load cells at base (orbiter-structure interaction)
- Distributed accelerometers (mode shapes & damping)
- Rate gyros from damper sets (lower mode data)
- Excitation by torque wheels from damper sets

264.964-37

2.5.2 DAMPING AUGMENTATION. Based on the predicted responses and damping times for the preliminary model (Table 2-12), it was concluded that 1% damping with augmentation may be sufficient and 2% damping is adequate, depending on the final configuration selected. For the first requirement, it should be noted that the amplitude buildup for lightly damped modes is a rather slow process even when the excitation is at the exact critical frequency. Three damping augmentation approaches were considered for the SCE. The alternative approaches are shown and compared in Figure 2-19.

Table 2-12. Variable Damping Ratio Effects on Tip Motion and Stabilization Time.

Damping Ratio	Steady-State Tip Motion, meters	Minutes to Stabilize
0.001	±11.4	87.0
0.01	± 1.2	8.7
0.02	± 0.6	4.3

264.964-38

Low frequencies, as will be encountered in the first mode of the test structure, are best damped with the torque wheel/rate gyro damper, which was used with dramatic success on a Convair IRAD program. Although the IRAD wheel starts limiting at 1.3 Hz, this frequency can be readily reduced by additional weight and size.

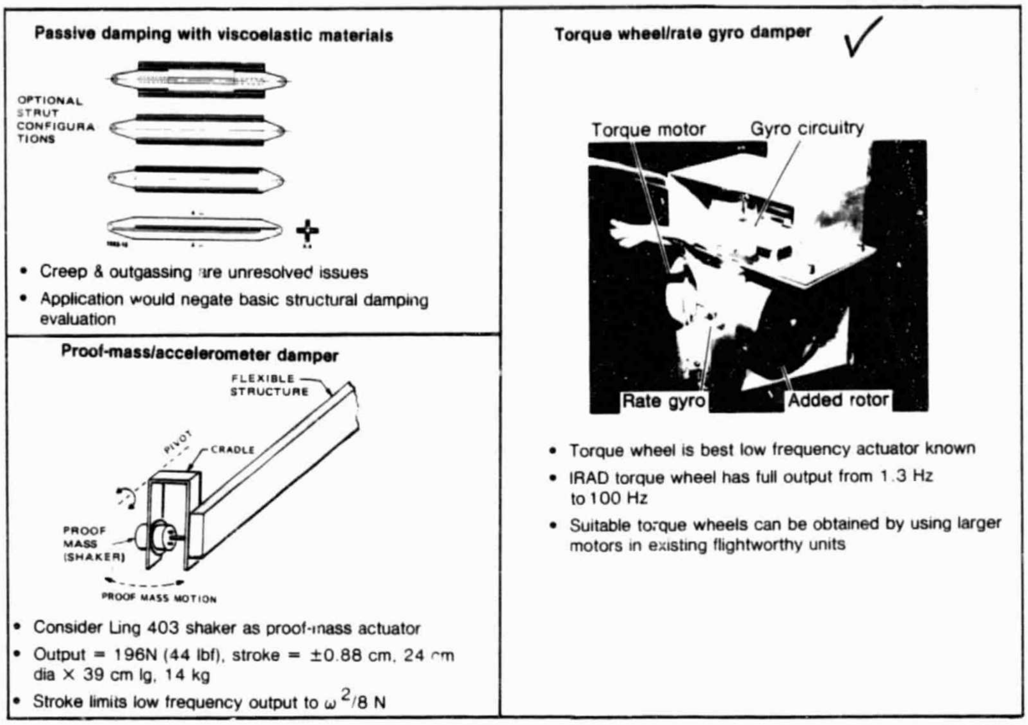


Figure 2-19. Candidate Damping Augmentation Approaches

The installation concept for the selected damping augmentation approach is shown in Figure 2-20. By using two torque wheel damper sets per axis with each set providing 1% damping to the first bending mode, it is possible to select 2% damping (both sets operating), 1% damping (one set operating), or zero added damping with both sets off. Sizing the maximum torque of the wheels is not especially critical since they still provide damping in saturation but not as much as when they are operating in the linear range. The installation shown includes provision for variable tip masses by pumping fluid into closed cylinders. Thus, between partial deployment and partial tip mass, the extreme condition can be approached in fine increments. Preliminary sizing indicates a maximum torque of 4.5 Nm as set by a 50 m truss and a 0.05 deg/sec step change in Orbiter body rate.

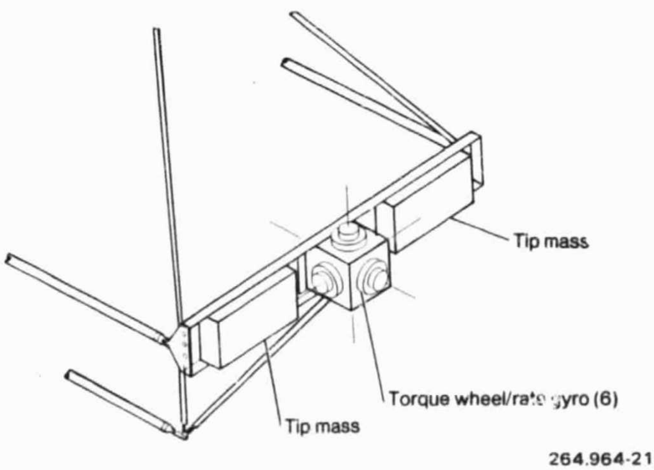


Figure 2-20. Recommended Damping Approach

2.5.3 DAP CONSIDERATIONS. The most complex interaction between the DAP and the SCE structure arises from large flexible structure with low modal frequencies and large moment of inertia contributions. As the structure grows

larger and the frequencies get lower, there is a limit to the ability of the DAP to maintain control. Attempts to identify and understand this limit have been given considerable emphasis in this program.

DAP performance is measured by achievable pointing accuracy and the rate of RCS propellant consumption. With the SCE structure designed for worst-case contingency loads, other performance limiters include deployed structure flexibility, deployment transients, products of inertia, center of mass shifts, and RMS operations.

Table 2-13. Simulation Run Summary for Preliminary 100 m Truss with 100 kg Tip Mass

	VRCS			PRCS		
Maneuv Axis	**Maneuv angle**	**Rate limit**	**Deadband**	**Maneuv angle**	**Rate limit**	**Deadband**
Roll	10 deg	0.02 deg/sec	1 deg	40 deg	0.3 deg/sec	5 deg
Pitch	10 deg	0.02 deg/sec	1 deg	40 deg	0.3 deg/sec	5 deg
Yaw	10 deg	0.02 deg/sec	1 deg			
R,P&Y	10 deg	0.02 deg/sec	1 deg			
Roll	10 deg	0.02, T<60 0.01, T>60	1, T<60 .1, T>60			

- Maneuver rate: 0.25 deg/sec VRCS; two deg/sec PRCS
- Also, one manual control case & two cases with primary jets failed open
- No really significant DAP performance degradation in any of the runs
- VRCS roll "clamp down" run, however, showed Nav base oscillation rates of two times the rate limit

264.964-39

A preliminary NASTRAN model of the SCE was prepared by Convair and transmitted to the Charles Stark Draper Laboratory (CSDL) on data tape. Table 2-13 summarizes the CSDL simulation runs. Although the 100 m beam with the 100 kg tip mass gave larger moment of inertia changes than any payload previously run at Draper, the conclusion was that the DAP could handle it without any significant performance degradation.

In an attempt to better understand the flexible payload/DAP interactions, data were assembled on other payloads simulated at CSDL (Table 2-14). The only payload that showed any signs of DAP performance problem was the one having the lowest bending frequency. This indicated the presence of some frequency-sensitive element in the system that attenuated the structure-induced oscillations of the Orbiter before they reached the jet logic.

Table 2-14. Flexible Payload Comparison

Payload	Lowest frequency (Hertz)	Deployed I_{xx} / Stowed I_{xx}
RMS-PEP	0.052	1.19
Space telescope	0.566	1.20
IUS/TDRS	0.127	1.18
IUS/Galileo	0.16	1.36
IUS/DoD1	0.097	1.25
Beam, 100m, 100 kg	0.14	2.00

Only the RMS-PEP displayed a significant increase in propellant consumption (21%)

264.964-40

The DAP State Estimator was identified as the frequency-sensitive element. Figure 2-21 shows the default filter gains - those gains the computer uses unless other values are specified. The 0.05 Hz oscillations of the RMS-PEP were cut in half by the filter, and this relatively low mass payload still caused a moderate increase in propellant consumption. Heavier payloads with a bending frequency of 0.05 Hz or less may have severe problems with the filter. Changing

the filter to start cutting off at a lower frequency would eliminate flexibility problems but could cause other problems due to rate information being too old when it reaches the phase plane logic. This is an area for further study. However, it is clear that if the SCE structure is to evaluate the proven limits of the DAP, the first mode bending frequencies must be lowered.

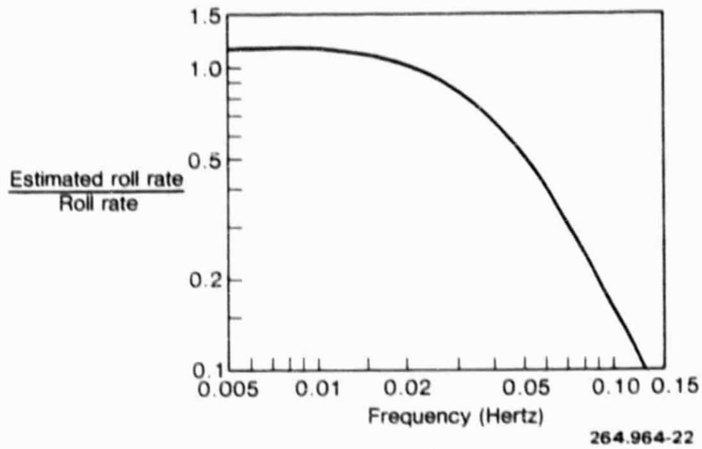


Figure 2-21. State Estimator Filter Characteristics

The use of a flexible mount was selected to reduce SCE bending frequency because it is the only approach identified that has no undesirable features or limitations. A NASTRAN data tape of the current SCE configuration with a range of base mount flexibility was sent to CSDL for simulation analysis to determine a minimum frequency for the experiment. The SCE design will be revised in the next study phase to achieve the required frequency.

2.6 PRELIMINARY TEST PLAN

The preliminary ground test program plan is summarized in Figure 2-22. The development testing phase will allow definition of system requirements for the program Phase C/D design and development effort. Flight qualification tests will verify flight worthiness, environmental compatibility, and functional capability of the SCE. Plans for flight test follow the flow as shown in Figures 2-23 and 2-24, with mission timelines as indicated. As seen from the timeline for Day 2, the actual amount of time available to perform construction operations is limited by the preparation, removal, and restowage/securing time.

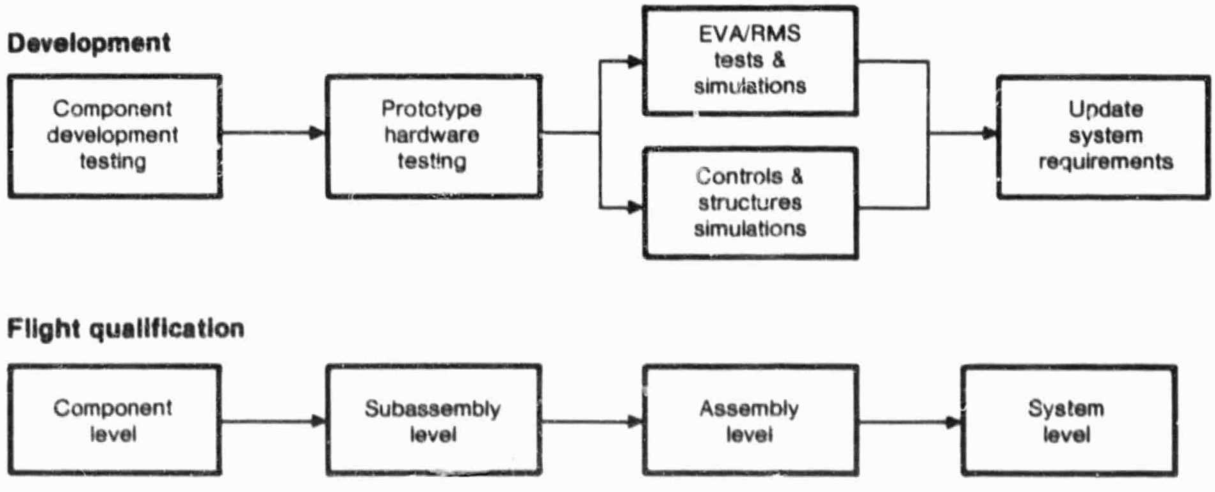


Figure 2-22. Ground Test Program Summary

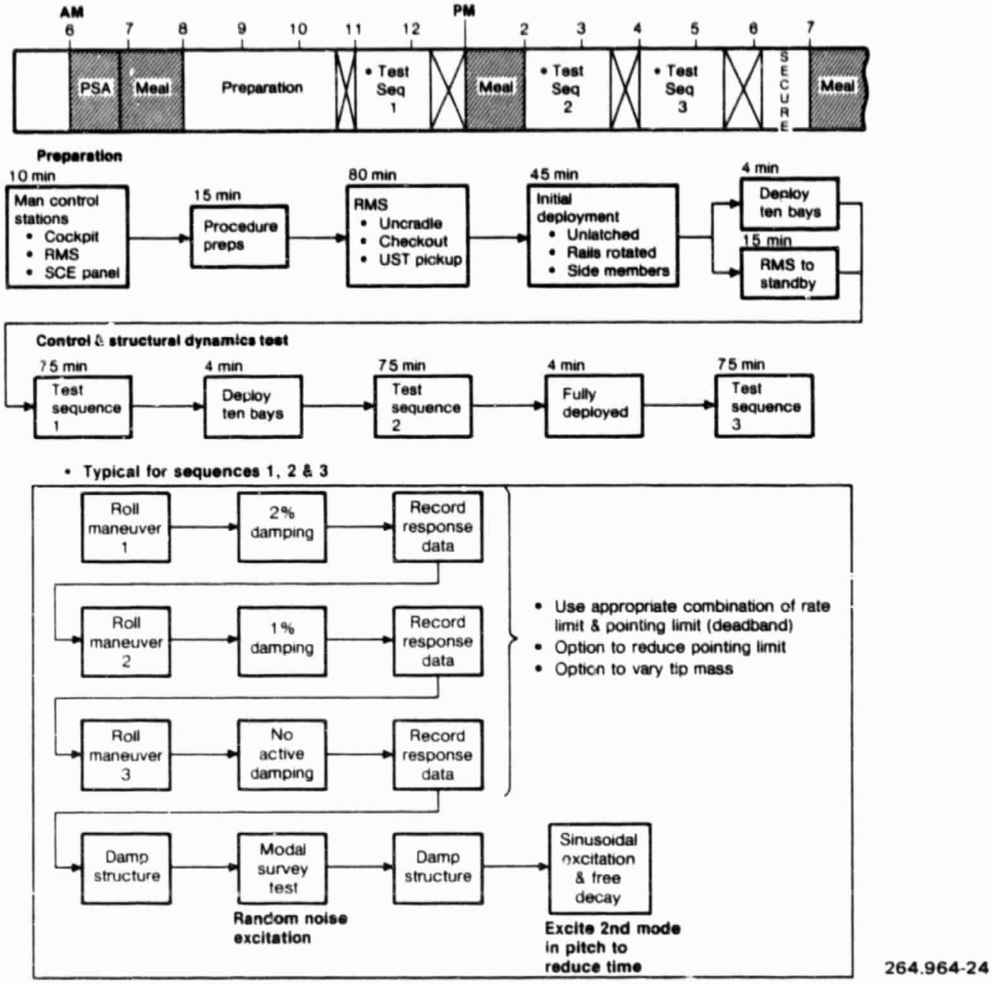


Figure 2-23. Flight Test Operations Sequence and Timelines for Day 1

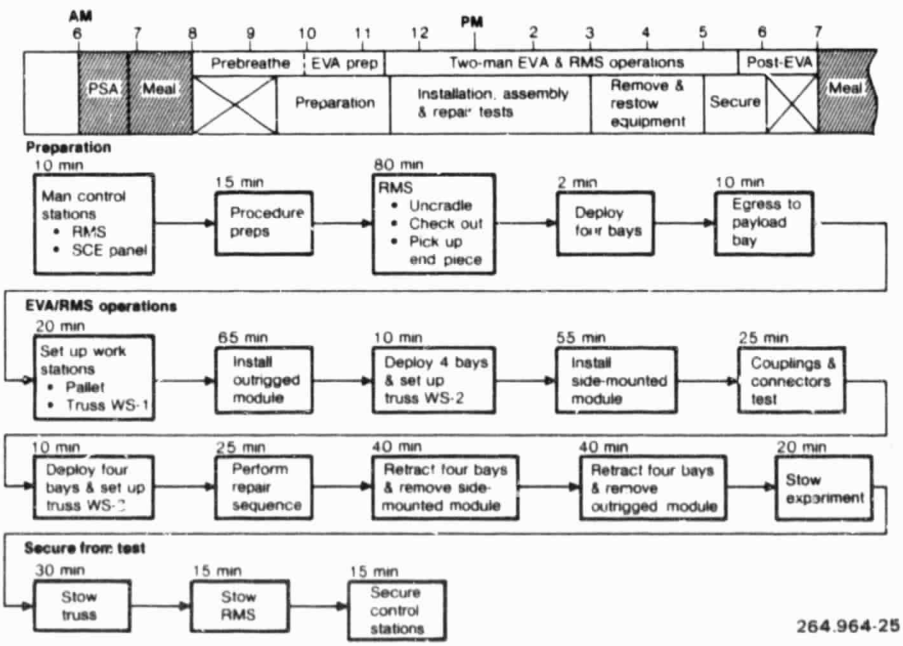


Figure 2-24. Construction Operations Test Sequence and Timelines for Day 2

2.7 PROGRAMMATICS

2.7.1 PROGRAM DEVELOPMENT PLAN. Based on the overall program scope of the SCE and the desired milestones, a summary program development schedule was established (Figure 2-25), which provides for a 24-month development program leading to the flight test in November 1984 as an earliest flight opportunity. The 24-month development period is judged to be tight but achievable if it is preceded by a Phase A/B definition phase in 1981 and certain ground tests and simulations in 1982.

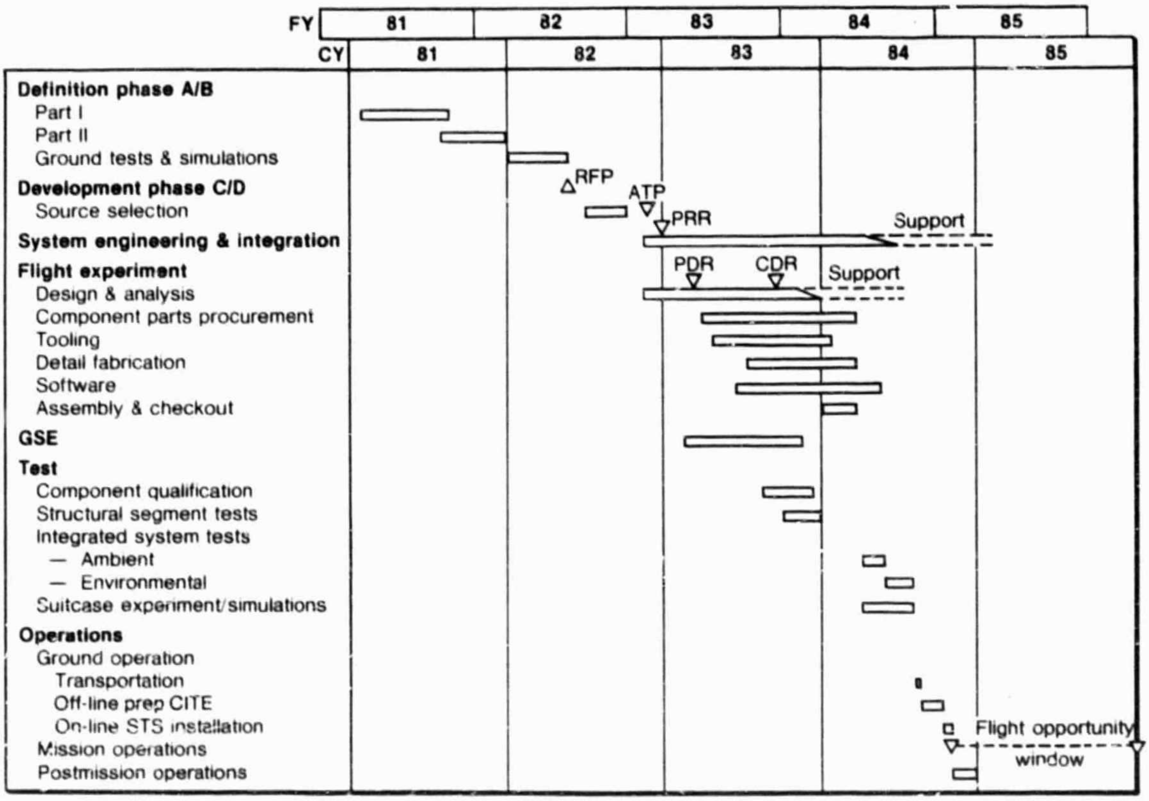


Figure 2-25. Preliminary SCE Program Development Schedule

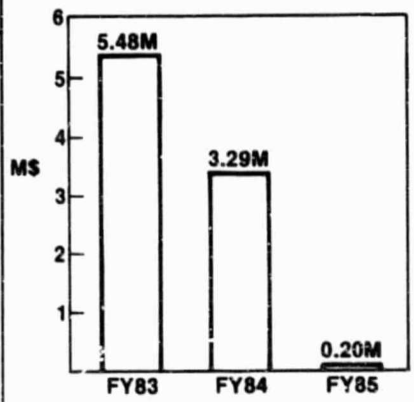
The Phase A/B information will provide refinement of selected concepts and tradeoffs. system design data including preliminary systems specifications, and a set of implementation plans including manufacturing, procurement, test, and reliability and safety areas. In addition, schedule and resource estimates will be produced. The principal outputs from these Phase A/B activities are validated requirements, a design solution and supporting analyses, program plans, and a preliminary estimate of resource requirements. The ground tests and simulations envisioned include RMS simulations and neutral buoyancy tests using the current truss hardware. This information will then provide a firm foundation for efficiently proceeding with the subsequent operational system C/D phase of activities.

2.7.2 PROGRAM FUNDING. Initially a cost-related work breakdown structure (WBS) was developed that includes all elements chargeable to the SCE project for each program phase. Following selection of the preferred concept from candidates examined (Concept 2A) in the first phase of the study, additional analysis provided increased design definition detail and refined input parameters used in the cost analysis. Using this updated information, new cost estimates were made for the selected SCE. Results of this analysis, general ground rules, and estimating assumptions are presented in Figure 2-26.

Cost summary (1981 $M)

	Design & development	Fabrication
Flight hardware		
• Structure	2.10	0.92
• Dynamic test equip	0.48	0.23
• RMS/EVA test equip	0.18	0.07
• Airborne support equip	1.98	0.33
• Assembly, integration, & c/o	—	0.09
Software	0.20	—
System eng & integration	0.43	—
System test	1.00	0.09
GSE	0.25	—
Spares	0.19	—
Facilities	—	—
Program mgmt	0.34	0.09
Total	7.15	1.82
Grand total	8.97	

Annual funding (1981 $M)



COST GROUNDRULES

- Costs are shown in constant 1981 dollars.
- Prime contractor fee is not included.
- Costs are for the design development and fabrication of a single, flyable experiment.
- All system testing required is accomplished using the flight article hardware.
- No mission operations or Shuttle user charges are included.
- The cost estimates presented are rough-order-of-magnitude costs for planning purposes only.

264.964-27

Figure 2-26. Program Funding Requirements.

The majority of the hardware design and development cost is required for structure and mechanisms including the truss itself, its deployment mechanism, and the supporting structure (FSE) for mounting the SCE in the Shuttle payload bay. The dynamic test equipment is considered as virtually all off-the-shelf (e.g., gyros and accelerometers) and very little in the way of component development will be required. Only a nominal cost allowance is required for the RMS/EVA test equipment in that there are mass and form mockups only to establish the feasibility of attaching equipment to the truss beam.

Operations costs have not been estimated but would consist of transportation (to KSC), ground operations required for STS installation and postflight disposition, and support activities during flight.

Annual funding requirements by fiscal year for development and flight article fabrication were generated by spreading individual cost elements in accordance with the program schedule.

SECTION 3

CONCLUSIONS AND RECOMMENDATIONS

3.1 CONCLUSIONS

3.1.1 STRUCTURE.

- Tetrahedral deployable truss has broadest range of applicability to future large space systems construction.

3.1.2 CONSTRUCTION OPERATIONS

- The cost, complexity, and uncertainties of performing full-scale ground tests make space testing of a deployable structural truss an essential first step to understanding and predicting performance and behavior of space structures attached to the Orbiter.
- Maximum use of the RMS for deployment operations greatly reduces systems cost and complexity.
- Controlled linear deployment of space structures is a major safety consideration, facilitates progressive assembly techniques, and allows control limits of the DAP to be approached slowly.
- Retraction capability will provide flexibility in selecting and performing experiment options, and reuse for future subsystems and construction aids testing.
- SCE will contribute to the understanding of structural rattle and backlash.

3.1.3 PRELIMINARY DESIGN

- SCE configuration and length are greatly dependent on primary mission payloads and payload arrangements.
- Up-to-date mission assignment data are required to confirm basic experiment design and capabilities.
- Fully deployed experiment jettison may pose a handling problem for the RMS.

3.1.4 ANALYSIS

- Near-zero CTE structure is achievable using graphite/epoxy fittings and tubes.
- Worst-case contingency loads impose structural cost, weight, and packaging efficiency penalties.

3.1.5 FLIGHT CONTROL ANALYSIS

- Flexible mounting of the structure will allow the DAP to be challenged, reduce loads in the structure, and allow structural frequencies to be adjusted.
- The key item in understanding large space structure/DAP interactions is the state estimator.
- Torque wheel/rate gyro type dampers at the tip of the structure provide variable damping and structural excitation capabilities most effectively.

3.1.6 TEST PLAN.

- Time for EVA experiments is severely limited by a one-day work plan.

3.1.7 PROGRAM PLAN

- Late 1984 flight is achievable if program start is initiated in early 1983 and a compatible mission is available.
- Total program cost is within the $10M maximum guideline.

3.2 RECOMMENDATIONS

3.2.1 SYSTEMS DESIGN AND ANALYSIS

- Further evaluate suitable missions for SCE accommodation and select best flights available.
- Obtain preliminary flight assignment for SCE.
- Further develop and define SCE preliminary design for Shuttle integration.

3.2.2 FLIGHT CONTROL ANALYSIS

- Analyze latest experiment model for a range of mounting stiffness/reduced modal frequencies.
- Select an appropriate mounting stiffness and reevaluate truss loads and sizing for prescribed contingency conditions using the Charles Stark Draper Laboratory dynamic simulation.
- Evaluate a slower state estimator in DAP simulation.

3.2.3 SYSTEM TEST.

- Prepare ground tests and simulations plans and initiate a ground test and simulation program to further develop system requirements.